Toward a Predictive Model of Arctic Coastal Retreat in a Warming Climate, Beaufort Sea, Alaska

PI: Cameron W. Wobus
Cooperative Institute for Research in Environmental Sciences
Campus Box 216
University of Colorado
Boulder, CO 80309
Phone: (303) 735-2413 Fax: (303) 492-2606 Email: cameron.wobus@colorado.edu

PI: Robert S. Anderson
Institute for Arctic and Alpine Research
Campus Box 450
University of Colorado
Boulder, CO 80309
Phone: (303) 735-8169 Fax: (303) 492-6388 Email: andersrs@colorado.edu

Co-PI: Irina Overeem
Institute for Arctic and Alpine Research
Campus Box 450
University of Colorado
Boulder, CO 80309
Phone: (303) 492-6631 Fax: (303) 492-6388 Email: irina.overeem@colorado.edu

Award Number: N00014-07-1-1017
http://spot.colorado.edu/~camerow/alaska.html

LONG-TERM GOALS

The long-term goal of this project is to understand the environmental drivers of extremely rapid coastal erosion in the Arctic, so that we can begin to predict how present and future climate change might influence coastal evolution. Our study is focused on the Beaufort Sea coast within the National Petroleum Reserve – Alaska (NPR-A), approximately halfway between Barrow and Prudhoe Bay. We are focusing our efforts on collecting empirical data that will help us to develop process-based models of coastal change. Toward this end, we are monitoring erosion processes using time-lapse photography, collecting meteorological and oceanographic data from sites along the coast, and archiving climatic and geographic data from the past few decades to identify trends in coastline position through time. We anticipate that our project will help us to predict future patterns of coastal change as a function of projected changes in sea surface temperature, sea ice conditions, and changes in land surface temperatures.

OBJECTIVES

Previous work documenting coastal change in the Arctic has been based primarily on descriptive analyses of coastal positions through time, with only circumstantial evidence of the processes driving rapid coastal change. Our main scientific objective is to combine detailed observations from

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE
30 SEP 2008

2. REPORT TYPE
Annual

3. DATES COVERED
00-00-2008 to 00-00-2008

4. TITLE AND SUBTITLE
Toward A Predictive Model Of Arctic Coastal Retreat In A Warming Climate, Beaufort Sea, Alaska

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Colorado,Cooperative Institute for Research in Environmental Sciences,Campus Box 216,Boulder,CO,80309

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Code 1 only

14. ABSTRACT
The long-term goal of this project is to understand the environmental drivers of extremely rapid coastal erosion in the Arctic, so that we can begin to predict how present and future climate change might influence coastal evolution. Our study is focused on the Beaufort Sea coast within the National Petroleum Reserve ? Alaska (NPR-A), approximately halfway between Barrow and Prudhoe Bay. We are focusing our efforts on collecting empirical data that will help us to develop process-based models of coastal change. Toward this end, we are monitoring erosion processes using time-lapse photography, collecting meteorological and oceanographic data from sites along the coast, and archiving climatic and geographic data from the past few decades to identify trends in coastline position through time. We anticipate that our project will help us to predict future patterns of coastal change as a function of projected changes in sea surface temperature, sea ice conditions, and changes in land surface temperatures.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**13**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

environmental monitoring and remote sensing to understand the *processes* driving rapid coastal erosion, and the primary *environmental drivers* leading to this change. Our planned and completed field data collection includes: 1) measurement of bluff substrate properties including ice content, ice-wedge polygon spacing, and the thermal properties of bluff materials; 2) time-lapse photography to observe coastal erosion processes in real-time; 3) establishment of a meteorological monitoring network to summarize the climatic forcings on the system; and 4) monitoring of nearshore conditions including bathymetry, wave fields, and sea surface temperatures. By synthesizing these field observations and remote sensing observations into process-based numerical models, we anticipate that we will be able to predict future patterns of Arctic landscape change in the face of changing climatic conditions.

APPROACH

Our technical approach can be divided into three components. The first component is to use historical remote sensing datasets to document changes in both coastal morphology and climatic conditions over the recent past. We are focusing our efforts on the relatively recent past (approximately the past decade), during which time we have the most substantial overlap between available environmental records and remote sensing of shoreline positions. Rates of coastal change over the past decade are being calculated using analyses of orthorectified satellite imagery, aerial photography, and GPS locations taken from the same site over multiple time slices.

To constrain numerical modeling of the offshore water and sediment dynamics, background oceanographic and bathymetric data is important input. However, measurements are inherently difficult in a sea-ice covered Arctic ocean and relatively limited continuously monitoring occurs. First-order input data on bathymetry, tidal energy and wave energy have been collected from previous mapping, monitoring and modeling efforts.

We have also assembled sea surface temperature (SST) data from the MODIS sensor over the past 8 years showing seasonal and annual variations in SST along the Beaufort Sea coast. Although the relatively low resolution of these data (4 km grid spacing) requires that we treat them as qualitative estimates of the sea surface temperatures along the immediate coastline, this dataset provides us with a view of year-to-year changes in the amount of heat available to drive thermal erosion of coastal materials. Finally, analysis of USGS data from meteorological and active layer monitoring stations along the coast provides us with a view of subaerial heat inputs to coastal bluffs that we believe to be important in preparing bluffs for more rapid erosion by thermal and wave attack along the coast. Previous investigators have used remote sensing to document changes in coastline position through time; our remote sensing approach has been to focus on the more recent past and to synthesize these visual observations with relevant climatic data to uncover the key environmental drivers of coastal change.

The second component of our technical approach is to collect on-the-ground data describing the material comprising coastal bluffs, the mechanisms of bluff failure, and the environmental conditions leading to failure events. The specific tasks that have been and will be undertaken as part of our on-the-ground data collection efforts include: 1) collection of samples from coastal bluffs to analyze for ice content, organic content (loss on ignition) and grain size; 2) measurement of size distributions of failed blocks and ice-wedge polygons on the ground; 3) measurement of near-surface thermal profiles distributed in both space and time; 4) installation of meteorological stations for long-term monitoring of weather conditions near the coast; 5) installation of wave sensors to monitor wave energy and storm

surges through the summer open-water season; and 6) installation of time-lapse photography to observe coastal erosion in real-time. Armed with these empirical datasets, we can then inform numerical models of how thermal energy penetrates different bluff substrates; what the fate of eroded material is once it enters the nearshore environment; and how erosion proceeds via thermal and mechanical avenues.

The third component of our technical approach is to develop physically-based numerical models of Arctic coastal erosion and sediment dynamics. Aerial imagery, environmental data, and field observations are being used to create empirically-based parameterizations of coastal retreat rate as a function of sea surface temperature, wind speed, and offshore sea ice position. Guided by data collected in the field, physics-based models of coastal erosion will be used to describe coastal change driven by thermally driven and mechanically driven erosion of coastal bluffs. Finally, modules describing specific littoral processes will be developed using Delft3D. We have begun developing models to describe the penetration of heat into the land surface and exposed bluff materials; and to describe the torque balance governing the eventual topple-failure of undercut coastal bluffs.

The personnel involved in these data collection activities are as follows: Analyses of satellite imagery and environmental data is being undertaken by PI Wobus with the aid of graduate student Nora Matell and undergraduate Cordelia Holmes. Our first round of field data were collected by Matell, Overeem, Anderson and Wobus during the summer of 2008, and will continue through the summer of 2010. USGS scientists Clow, Urban and Jones assisted with retrieval of sensors during the 2008 summer season. Wave sensors were built by collaborator Tim Stanton at the Naval Postgraduate School in Monterey, to be deployed in summer of 2009 (see below). Numerical modeling has been led by co-PIs Anderson and Overeem, with thermal modules developed by Matell.

WORK COMPLETED

During the academic year prior to this annual report, we collected and processed remote sensing data from available archives, began our numerical modeling efforts to describe the relevant thermal and mechanical processes contributing to coastal change, planned and implemented our first field season, began processing meteorological and sedimentological data from the field, and submitted two abstracts for the AGU annual meeting in December. During this period, we also built upon valuable collaborative relationships with colleagues at USGS which have improved our ability to streamline data collection efforts across multiple institutions.

1. Collection, archiving and processing of existing environmental data

The first task completed in the fall of 2008 was a search of archived datasets for both remotely sensed imagery of the Beaufort Sea coast and for satellite observations of sea surface temperature and relevant meteorological conditions. We obtained aerial photographs from 1955, 1976 and 1979, as well as Landsat imagery from 2002 and Corona spy imagery from 1966. These images summarize coastal change over the latter half of the 20th century; we are currently in the process of obtaining high-resolution satellite imagery from the past 8 years showing changes in coasline position through the more recent past.

Sea surface temperature (SST) data were obtained from the MODIS sensor, and were imported, clipped, reprojected and processed to extract timeseries of SST for the Beaufort Sea. Algorithms were written to digest new data as they become available, and to distill these data into datasets illustrating

the relevant portions of the Beaufort Sea most proximal to our field area. These images clearly show spatial and temporal variability in sea surface temperatures along the Beaufort Sea coastline through the summer open-water season, including the thermal influence of shallow waters nearest the coast. Year-to-year comparisons of these datasets also illustrate pronounced interannual variability in sea surface temperatures. Our preliminary observations suggest that the the warmest SST records correspond to years in which extremely rapid coastal change has already been documented.

Basin-scale bathymetric data are available from the GEBCO bathymetric grid. This is a 3D interpolation of unevenly distributed bathymetric information. The bin size of the global grid is 1 by 1 arc minute and it is based on digitized bathymetric contours supplemented by individual echo soundings. The horizontal resolution is approximately 2 by 2 minutes and the vertical resolution is ~ 0.5% of the water depth. The grid is not designed for mapping shallow water features, since the original contour data consisted of 100 m intervals. Detailed bathymetry for this area are available from NGDC/National Ocean Service, Hydrographic Surveys database. Survey H07921 was done by the US Coast and Geodetic Survey, covers Smith Bay and the nearshore area of Drew Point, and dates back to 1951-1952.

We used WXTIDE to analyze station-by-station tide data based on the modeling of harmonic tides. Data analysis of three available stations provide mean range (in m), maximum tide, and statistical distributions over 30 years. The stations are located at Point Barrow, and Prudhoe Bay. Mean tidal range is a first-order parameter to assess tidal energy; calculated mean range is 0.08m for Point Barrow, and 0.14 and 0.15m for Prudhoe Bay buoys. Although there is a slight influence of tidal setup to be expected, we assume the influence is negligible for the first-order experiments. WaveWatch III provides yearly simulations of 3-hour averages for storm climate and generated waves for the entire world. These model data have been processed in GIS, and we calculated monthly statistics for wave height and wave power for relevant coastal pixels. Only a limited stretch of the Arctic coastline is covered by the dataset, due to difficulty of modeling sea-ice and wave interactions.

The limited availability of oceanographic data in the near-coastal Beaufort Sea area underscores the importance of in-situ monitoring. We have collaborated with Dr Tim Stanton at the Naval Postgraduate School to develop buoys equipped with pressure transducers and strings of sea water temperature sensors.

2. Field Data Collection

In June of 2008, we completed our first full field season along the Beaufort Sea coast. Our main objectives were to 1) collect data describing the stratigraphy, ice content, and spatial variability of coastal bluffs materials; 2) to begin our long-term meteorological monitoring; and 3) to establish time-lapse photography installations to observe coastal erosion processes in real-time. Although we encountered some unforeseen challenges during our field work, we were successful in establishing our ground-based monitoring stations, collecting data describing the thermal properties of the coastal bluffs, and deploying three time-lapse photography installations to observe coastal processes in both marine and lacustrine environments.

A. Coastal Stratigraphy – One of the advantages of arriving on the North Slope early in the summer was the ability to walk on snowdrifts along the base of coastal bluffs to record stratigraphic information and to collect samples. We found that the subsurface stratigraphy along the coastline is relatively consistent along the shoreline, despite pronounced differences in the surface appearance of

drained thaw lakes and adjacent segments of patterned ground. In particular, the ice wedges that define the polygons across much of the North Slope are also present in the subsurface beneath drained thaw lakes. The depth to which surficial thaw lakes perturb this stratigraphy appears to vary with the size of the lakes (see modeling results below); but can be as little as 0.7 meters. We collected representative samples from the most consistent stratigraphic layers that are currently being processed for ice content, organic content, and grain size. These data will help us to inform models of both coastal erosion by thermal processes and of the fate of eroded material in the littoral environment.

B. Establishment of Long-term Monitoring – One of our major objectives during this field season was to set up long-term meteorological stations to monitor climatic parameters that might be driving coastal erosion in the Arctic. Toward this end, we set up a meteorological station at Drew Point to record temperature, barometric pressure, wind speed and direction, and ground temperatures year round. We also constructed a station along the western shore of Lake 31, which is approximately 15 km inland and serves as a natural experiment for monitoring coastal erosion by purely thermal processes. This station also records temperature and wind speed and direction, and is also outfitted with a time-lapse camera. Both stations are outfitted with radios so that they can stream data and imagery in near-real time via the USGS telemetry network.

C. Time-lapse photography – We set up three time-lapse cameras during our summer field season to observe coastal erosion processes. Two of these cameras were set up along the coast near Drew Point, and the third was deployed along the shore of Lake 31. Imagery from all three of these cameras has been retrieved, and time-lapse movies have been developed from the image sets. These time-lapse movies have been instrumental in helping us to understand the drivers of coastal erosion along the Beaufort Sea, and are also becoming a key outreach tool for the general public.

D. Wave monitoring – We deployed to the field in June of 2008 equipped with four wave sensors, a Zodiac inflatable boat, and a depth sounder for bathymetric surveying. The goal was to deploy these wave sensors for a full open-water season from June through August to record total incoming wave energy to the shoreline through this period. Unfortunately, the sea ice at Drew Point remained in place unusually long this summer, making our deployment plans too dangerous to undertake. We have begun conversations with both logistics providers and with Dr. Stanton at NPS to evaluate alternative deployment strategies for next summer that might be less risky. We will keep ONR informed of these ideas as they materialize.

3. Numerical Modeling

A. Modeling Oceanic Coast Evolution – Stimulated by observations of the landscape in the field, and of our time-lapse images, we have begun to address the physics of the notching and block toppling of the coastal bluffs. This can be broken into two pieces: the melting of a notch, and the conditions of failure through a torque balance. In analogy with melting of icebergs, the notching rates are set by the temperature of the seawater at the coast. The vertical profile of the notch generated by melt will in turn be dictated by the probability distribution of the waves that deliver warm water. We therefore require algorithms for determining the local sea temperature and the amplitude of the waves through the summer, and the ice content of the coastal bluffs as a function of position in the stratigraphy and as a function of position along the coast. If the waves also serve to alter the degree of mixing of heat within the near-coast waters, the coast become particularly and nonlinearly susceptible to times in which the ocean is both warm and wave-filled. The topple problem reduces to a torque balance around a moving pivot point. The pivot propagates as the notch is inserted into the coastal bluff, placing more

and more of the coastal bluff outside of the pivot. When the torque associated with the overhang exceeds that provided by the tensile strength of the materials, failure will occur. Field observations suggest that the failure plane is often the join between ice wedges and polygon centers, which effectively leads to the distinct selection of failure block widths.

C. Modeling Lake Coast Evolution – Some of the most dominant geomorphic features on the North Slope are the numerous thaw lakes dotting the landscape. These thaw lakes are being used as a natural laboratory for testing our theories about the driving factors behind coastal erosion. We have documented significant erosion along the shores of thaw lakes with the use of time-lapse cameras. The lake coastline differs qualitatively from the sea coast in several ways. The land adjacent to the shoreline of Lake 31 is only 1 m above the level of the lake, as opposed to the 3-4 m tall bluff edge on the Beaufort coast. The notch generated by the lake is narrower, undermining the coastline by up to 2-3 meters with a notch only 20 cm tall. This presumably reflects the smaller waves in the lake, which in turn is dictated by the much shorter fetch. The resulting failure of the coast is also different; it is accomplished not by block topple, but by slow flexure of the overhang, drooping into the lake as a landward propagating wave. We hypothesize that the difference largely reflects the role of the vegetated mat, with roots that provide a finite resistance to bending. The physics therefore becomes dominated by bending rather than discrete failure.

To get a long-term perspective on how lakeshore erosion is occurring, we have processed Landsat images from 1979 and 2002, permitting us to calculate area differences between individual thaw lakes over this time period. These images make it clear that the lakes are not static; changes varied between lakes but included expansion, shrinkage, and complete drainage. Pairwise comparisons between medium size (>40 ha) lakes that existed in both images indicates that the average change in area was an increase of ~12%.

D. Thermal Modeling – The presence of these thaw lakes is so ubiquitous that it seems logical that they would also affect coastal erosion rates when intersected. In fact, in many places along the Alaskan and Canadian coasts they are clearly influential, forming incut bays where breached. A time series of aerial photos and images implies that coastal erosion rates over the past 50 years may have been higher in a large drained thaw lake. During fieldwork, we noted that the ground surface of this drained thaw lake was several meters lower than the surrounding tundra. However, other drained thaw lakes in the area were only several 10s of centimeters lower than surrounding tundra and did not exhibit higher erosion rates. Observations of coastal bluffs indicated that the subsurface influence of the shallow lakes was only ~70 cm in contrast to total bluff heights of ~4 m.

Our working hypothesis is that thaw lakes will only influence coastal erosion if their original depth was a significant percentage of coastal bluff height. We are thus working to understand the thermal perturbation of these lakes upon the underlying substrate, ultimately working towards understanding controls on lake depth. We are in the process of developing a numerical model which will combine permafrost thermal profiles with overlying lake water and ice, and which will permit subsidence of the land surface due to the melting of ground ice.

RESULTS

1. Remote Sensing

Our remote sensing efforts have brought us two valuable pieces of information: first, compilation of satellite and airphoto imagery has allowed us to construct our own timeseries of coastal position through time, focused on the Drew Point coast. This has helped to inform our understanding of how coastal erosion rates have changed through time, and how spatially variable these erosion rates have been, particularly with respect to thaw lakes of varying sizes. This is in turn informing our understanding of thermal models of permafrost. Figure 1 shows the results of our remote sensing compilation for Drew Point.

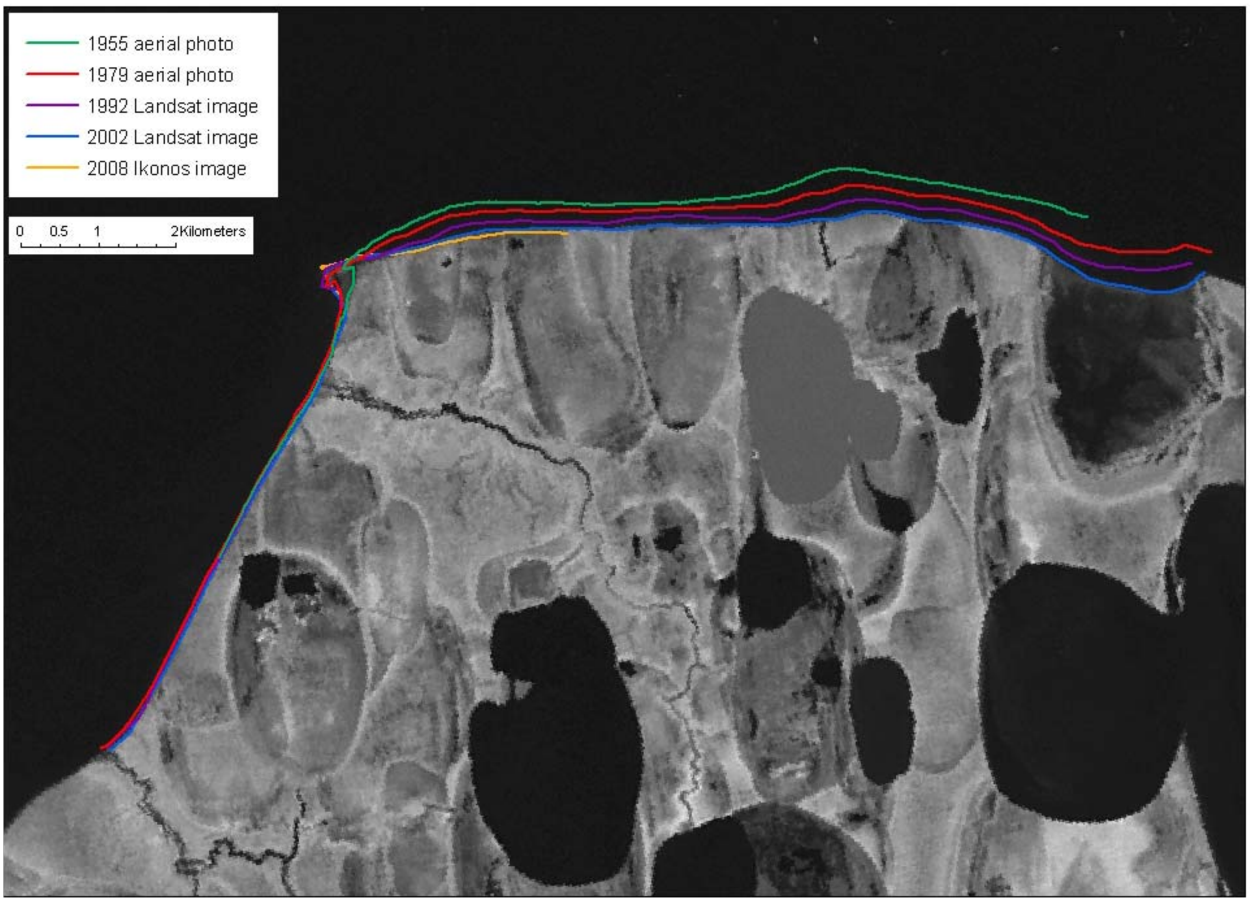


Figure 1. Coastal erosion along the Drew Point stretch of coast over the last 50 years. Note that the coastline intersecting the large drained thaw lake in the upper right of the image appears to have become progressively more indented, while other drained thaw lakes do not seem to have influenced coastal erosion.

2. Oceanographic conditions

The processed bathymetric data reveals a very shallow near-shore zone for our study area (Figure 2) and Smith Bay. Water depths generally are <4 m within the first 20 km offshore, and drop to ~ 6 m at 40 km offshore. Lateral variation in the coastal slope profile is relatively limited, implying a 2D cross-shore profile modeling approach is potentially a viable simplification.

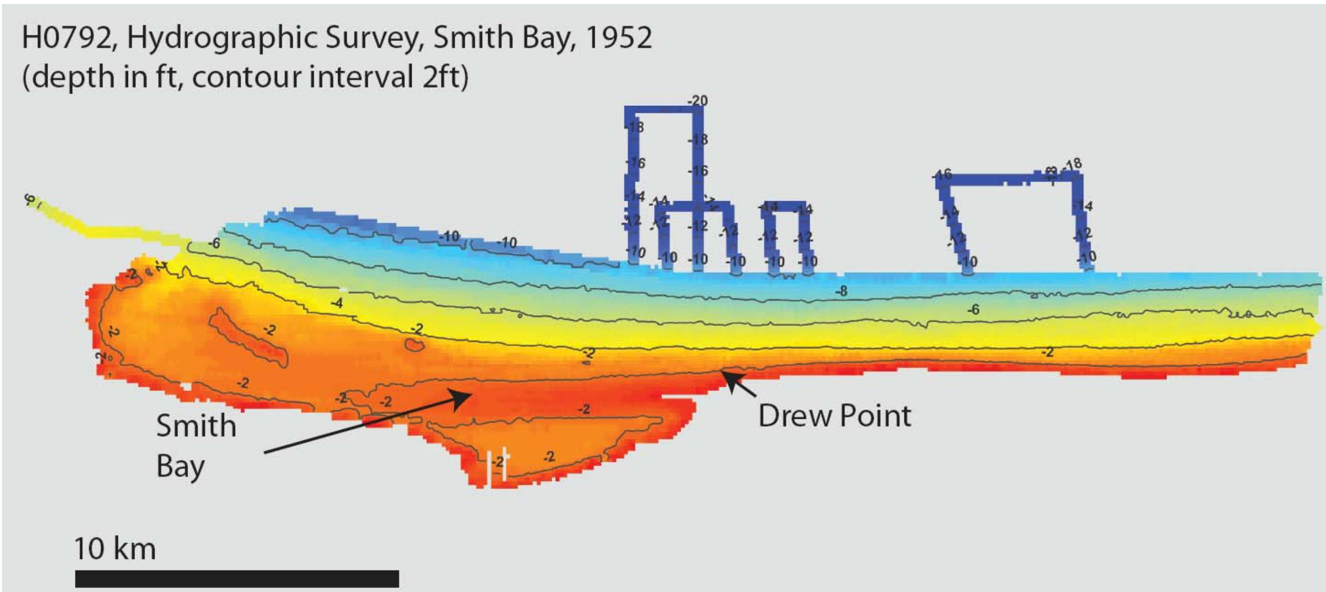


Figure 2. Detailed bathymetry based on Hydrographic Survey H07921, 1952 (NGDC/NOS data).

Tidal energy is retrieved from 3 buoys along the Alaskan Beaufort Sea and modeling of harmonic tides. The stations are located at Point Barrow, and Prudhoe Bay. Mean tidal range is a first-order parameter to assess tidal energy; calculated mean range is 0.08 m for Point Barrow, and 0.14 m and 0.15m for Prudhoe Bay buoys. Although there is a slight influence of tidal setup to be expected, we assume the influence is negligible for the first-order simulations. Analysis of WaveWatch III 3 hrs simulation for 2000 gives an indication of wave climate. Full monthly data is available only for July and August. Reconstructed significant wave heights are: 0.56m +/- 0.36 in July and 0.66m +/- 0.29m for August. We will further enhance existing wave data analysis to reconstruct a longer time-span data set.

Sea-ice data sets have been obtained from NSIDC DMSP SSM/I Daily and Monthly Polar Gridded Sea Ice Concentrations in polar stereographic projection from the Defense Meteorological Satellite Program -F8, -F11, and -F13 daily and monthly sea ice concentrations. This data is gridded at a resolution of 25 x 25 km, beginning 25 June 1987 and ongoing. We identified resolution problems with the near-coastal ice predictions, but continue to use these records to correlate with the coastal erosion processes.

A compilation of sea surface temperatures from the past nine summer seasons has been reconstructed based on satellite data. These data have been valuable in helping us understand the intra-seasonal and inter-annual variability in sea surface temperatures in the Beaufort Sea. We view these data as semi-quantitative, since the resolution of the MODIS satellite data is only 4 km and they therefore do not

capture locally high temperatures against the Beaufort Sea coast. However, these data can now be queried to evaluate patterns in SST through the summer, and to understand which summers stand out as having particularly warm SST. Interestingly, our preliminary examination of these data indicate that the summers of 2004 and 2007 were particularly warm during late July through mid-August. Anecdotal evidence suggests that these summers also had particularly rapid coastal erosion. Further quantification of this anecdotal evidence is ongoing.

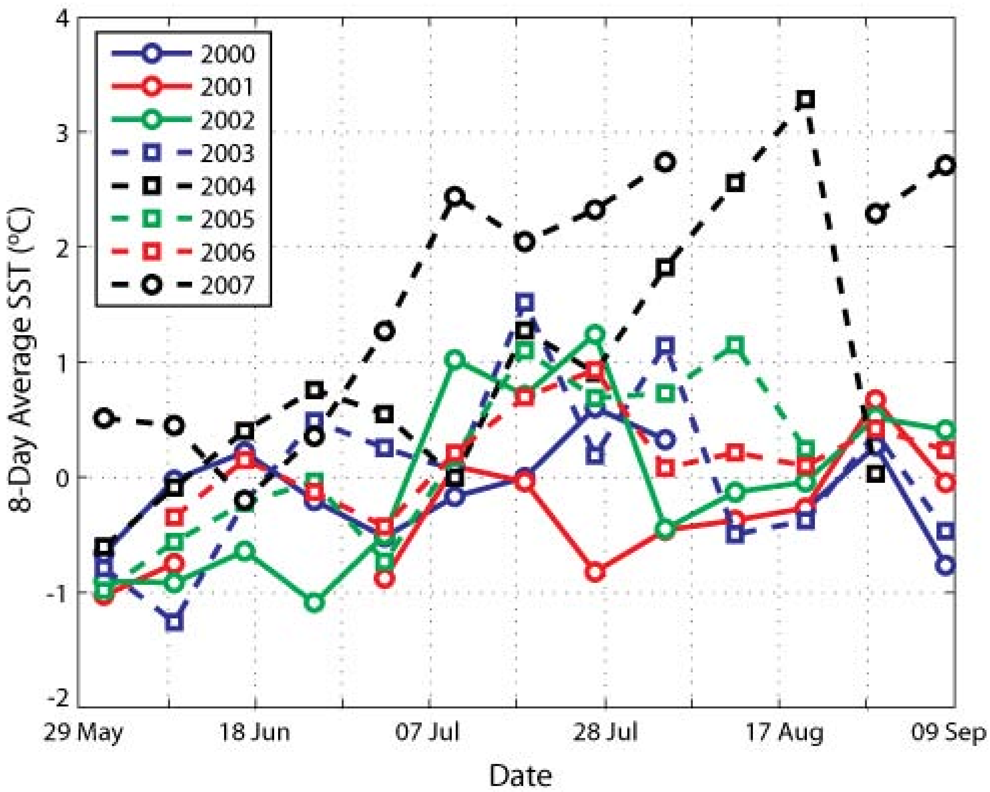


Figure 3. Compilation of 8-day averaged SST in swaths extending north from Drew Point, from summer 2000 through summer 2007. Note that the summers of 2004 and 2007 stand out as having particularly warm sea surface temperatures, which may correlate with rapid coastal erosion during these years.

2. Field Data Collection

The most influential datasets we obtained during our summer field work were three sets of time-lapse movies illustrating coastal erosion processes along the Beaufort sea coast and the shore of Lake 31. These images underscore the role that purely thermal erosion can play in undermining coastal bluffs, and illustrate how quickly the ice-rich blocks near Drew Point can be melted away once they topple into the sea. Figure 4 below shows three successive images from one of our time-lapse cameras at Drew Point. These images, and others like it, are helping to focus our thinking about the importance of discrete storm events vs. slow, steady disintegration of the coastal bluffs by thermal processes.

Figure 4. Three successive time-lapse photos collected on July 21st, July 22nd, and July 28th, showing the topple-failure and melting of a block of coastal bluff into the sea. Note that the entire process is complete within a week, and that no major storms occurred during this time period. Length of overhang in the first photo is approximately 2 meters.

We have also begun to process the meteorological data records from the two stations we set up on the North Slope. These data streams will continue to provide near real-time meteorological observations, which in combination with our field observations and numerical models will help us to quantify the major drivers of coastal change on the North Slope. Figure 5 shows an example of a 7-day data stream that can now be downloaded instantaneously via the USGS telemetry network.

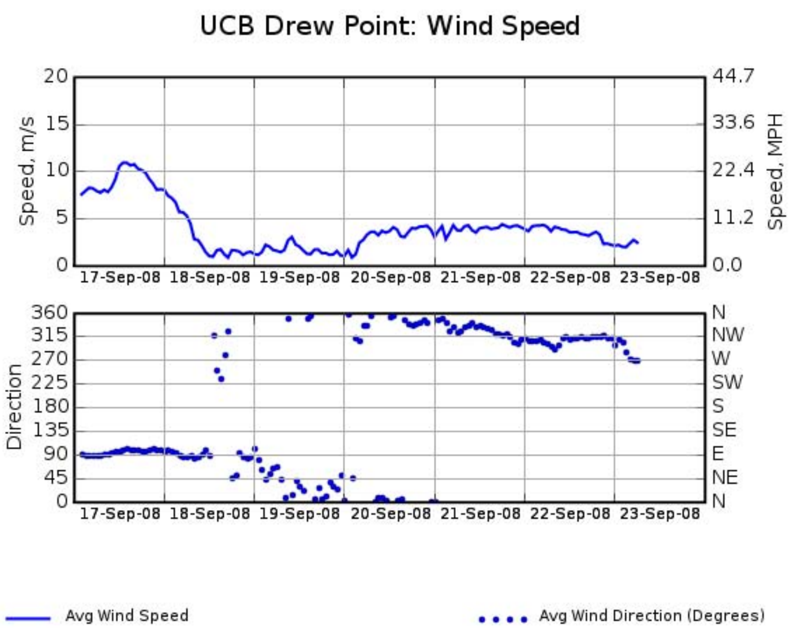
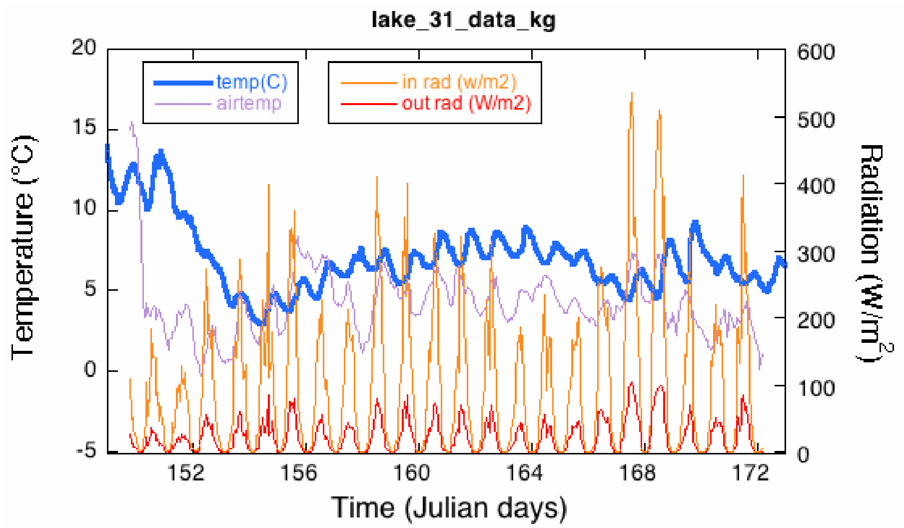


Figure 5. Example file showing 7-day wind speed and direction data from the new UCB Drew Point meteorological station. Data can be streamed daily via the USGS telemetry network

We have also collected data on incoming and outgoing solar radiation, air temperatures, and water temperatures at our Lake 31 site to quantify the thermal processes that drive the disaggregation of coastal bluffs and their eventual failure. Figure 6 shows data from Lake 31, where each of these data streams has been superimposed to enable us to understand how factors such as insolation, wind, and storm events influence shallow water temperatures. Note that in this case the temperatures in Lake 31 (shown in the thick blue line) drop substantially during a late July storm event (Julian Days 150-155), and do not recover again following this storm. Data such as these are helping us to understand how

physical mixing in shallow lakes and the nearshore environment might influence water temperatures against coastal bluffs, thereby affecting their ability to erode by melting along the bluff base.

Figure 6. Example of water temperature, air temperature, and solar radiation at Lake 31, spanning a late summer storm between Julian days 150-155. Note the dramatic drop in lake temperatures, possibly due to mixing of colder waters by wind energy.



Finally, we are processing our stratigraphic samples from coastal bluffs for grain size, ice content, and ^{14}C to get a better sense of the timing of deposition, thaw lake development, and ice-wedge formation. While we do not yet have complete data to report, preliminary measurements suggest that these bluffs may be as much as 75% ice by weight, which has significant implications for their ability to withstand thermal perturbations as well as for the fate of eroded material once it enters the nearshore environment.

3. Numerical Modeling

Our most substantial headway in numerical modeling has been into understanding the mechanisms of bluff failure and the penetration of thermal energy into the Arctic landscape. We have developed simple modules to describe the thermal notching along the base of coastal bluffs, which can be fed with empirical observations on sea surface temperatures, storminess, and sea ice position. These modules are an important starting point that will be compared with our data describing bluff ice

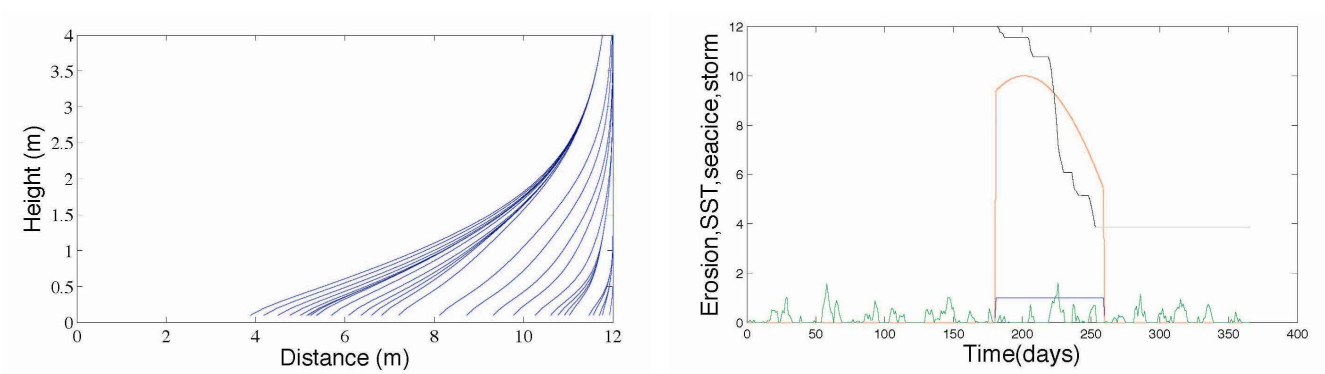


Figure 7. Left: modeled profiles of a seacliff through time, eroding right to left. Initial cliff is vertical at 12 m. Bottom: environmental drivers of eroding bluff, including time series of seaice (blue: 0=attached to coast, 1 = not), SST*seaice (red), storminess (green), and minimum x-position of coast (black).

content, sea surface temperature evolution, and erosion rates through time. Figure 6 shows output from one of these simple modules, illustrating how thermal notching proceeds given a set of environmental conditions.

We have also made progress in modeling the thermal evolution of frozen ground in the subsurface. These efforts have been focused on understanding the evolution of thaw lakes; but these modules will be equally applicable to modeling the penetration of thermal energy into frozen bluffs. Our final numerical model will combine permafrost thermal profiles with overlying lake water and ice, and will permit subsidence of the land surface due to the melting of ground ice. Thus far, we have developed and validated the first module, the permafrost thermal profile model. The module successfully reproduces ground temperatures measured at a USGS meteorological station near our Drew Point field site (Figure 8). the lake ice and subsidence modules are currently in the process of being validated.

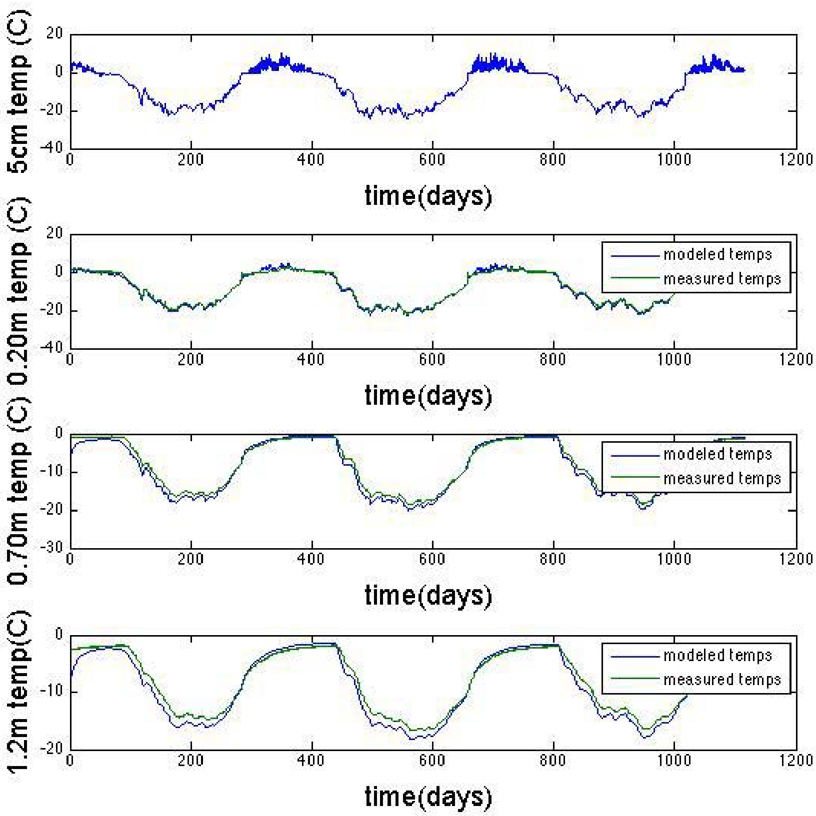


Figure 8. Measured and modeled ground temperatures at the Drew Point USGS meterological station. 5 cm soil temperatures (top panel) were model input data; modeled temperatures at depth are plotted along with measured temperatures in lower three panels.

4. Outreach

In addition to our science goals, we also set out on this project with the goal of relaying our science to the general public. Over the past six months we have made two very tangible contributions in this regard. While we were in the field, we participated in an International Polar Year (IPY) “Live from IPY” event sponsored by Polar TREC, in which K-12 teachers from around the United States were able to ask us questions via web chat or telephone. We described our research, our field setting, and our observations to the group, and had very positive feedback from the IPY organizers.

More recently, we developed a short video clip from our time-lapse photography showing a section of Beaufort Sea coastline being undermined by thermal notching and collapsing into the sea. Our CIRES outreach coordinator pitched this story to Andrew Revkin of the New York Times, and he posted our video on his "Dot-Earth" website. Judging from the comments that were posted on his website beneath the video, it is clear that Revkin's presentation has stimulated conversation in the environmental "blogosphere." We feel that this is one of the most direct ways our research has been communicated to the public to date, and we hope to continue to develop relevant outreach materials from our future research results.

IMPACT/APPLICATIONS

Our field data and observations to date validate the hypothesis that both thermal and mechanical energy are driving coastal erosion in the Arctic. These observations underscore the potential for continued very rapid landscape and seascape change in the Arctic: if climate change drives continued increases in sea surface temperatures, coastal erosion rates may continue to increase. In areas where coastal retreat is primarily a thermal problem, our observations might have important implications for our ability to predict future rates and patterns of coastal change. For example, models which predict future changes in sea surface temperatures might provide a simple means of predicting future rates of coastal change in ice-rich environments.

RELATED PROJECTS

PI Anderson and co-PI Overeem are both members of the Community Surface Dynamics Modeling System (CSDMS) terrestrial working group (http://csdms.colorado.edu/index.html). We anticipate that our project will tap the broader expertise of the CSDMS consortium as we move into the modeling component of our study. Photos of the eroding permafrost coast at our field site have been added to the Educational Gallery of the CSDMS: http://csdms.colorado.edu/wiki/index.php/Coastal_GL4

PIs Wobus and Anderson are both involved in an NSF-sponsored project to understand weathering in alpine environments. Thermal models of ground temperatures as well as technologies developed for monitoring weather conditions, collecting time-lapse photographs, and deploying self-contained temperature probes are creating synergies between these two projects.